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Size-dependent fracture toughness of bulk metallic glasses

Bernd Gludovatz [a], Steven E. Naleway [b], Robert O. Ritchie [a,c], Jamie J. Kruzic [b,*]

[a] Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[b] Materials Science, School of Mechanical, Industrial, and Manufacturing Engineering, Oregon State University, Corvallis, OR 97331, USA
[c] Department of Materials Science and Engineering, University of California, Berkeley, CA 94720, USA

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Abstract

The fracture toughness is a critical material property that determines engineering performance. However, as is well known for crystalline materials, if certain sample geometry and size requirements are not met, test results become sample-size dependent and difficult to compare between different studies. Here, the room-temperature fracture toughness of the Zr-based bulk metallic glass (BMG) $Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$ (Vitreloy 105) was evaluated using compact-tension, as well as single-edge notched-bend, specimens of different sizes to measure K_{Ic} values according to ASTM standard E399 and J_{Ic} values according to ASTM standard E1820. It is concluded that the ASTM standard E399 sample-size requirements should be cautiously accepted as providing size-independent (valid) K_{Ic} results for BMGs; however, it is also concluded that small-sized samples may result in a wider scatter in conditional toughness K_Q values, a smaller yield of valid tests and possibly somewhat elevated toughness values. Such behavior is distinct from crystalline metals where the size requirements of ASTM standard E399 are quite conservative. For BMGs, K_Q values increase and show a larger scatter with decreasing uncracked ligament width b, which is also distinct from crystalline metals. Samples smaller than required by ASTM standards for K_{Ic} testing are allowed by the J-integral-based standard E1820; however, in this study on BMGs, such tests were found to give significantly higher toughness values as compared to valid K_{Ic} results. Overall, the toughness behavior of BMGs is more sensitive to size requirements than for crystalline metals, an observation that is likely related to the distinct size-dependent bending ductility and strain softening behavior found for metallic glasses. It is concluded that toughness values measured on BMG samples smaller than that required by the K_{Ic} standard, which are common in the literature, are likely sample size- and geometry-dependent, even when they meet the less restrictive valid J_{Ic} requirements.

Keywords: Bulk metallic glasses; Fracture toughness; Sample size; Strain softening; Bending ductility

1. Introduction

Bulk metallic glasses (BMGs) are a class of engineering materials with unique properties, such as near-theoretical strength, low stiffness and the ability to be thermoplastically formed into precision-shaped parts with complex geometries [1–5]. Despite their useful combination of properties, the fracture toughness of these materials can sometimes be low and a limiting factor when considering BMGs for structural applications. For example, some early glasses are known to fail in a highly brittle manner, with K_{Ic} values as low as ~ 2 MPa m$^{1/2}$ [6]. In stark contrast, recent developments in specific Pd-based and Zr-based glasses have shown multiple shear band formation, subcritical crack growth and increasing fracture resistance with crack extension (i.e. rising fracture resistance curve (R-curve) behavior), with reported fracture toughnesses of up to ~ 200 MPa m$^{1/2}$ [7,8]. While such very low and very high fracture toughness values are certainly extremes for brittle

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[*] Corresponding author. Tel.: +1 541 737 7027; fax: +1 541 737 2600.
E-mail address: jamie.kruzic@oregonstate.edu (J.J. Kruzic).

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and tough fracture behavior of BMGs, most metallic glasses are reported to lie somewhere between 10 and 100 MPa m$^{1/2}$ [9–17]. However, there is often significant variability in the results, even within a single study. While some variability between studies may be explained by factors such as the use of notched vs. pre-cracked samples[1] [19,20], the influence of other parameters, like processing history and/or sample geometry, remain less clear.

A commonality among the very high toughness BMGs is the ability to form significantly more shear bands as compared to lower toughness glasses [7,8]. Conner et al. have shown a similar positive correlation between high numbers of shear bands and high ductility for Zr-based metallic glass plates subjected to bending [21,22]. While thick plates of BMG are well known to fail catastrophically in bending without significant plastic deformation, in the Conner et al. studies plates with thicknesses, t, of less than 1.5 mm were bent in a ductile manner around dies of different radii, r, showing increased shear banding (smaller shear band spacing, λ) and increased ductility prior to fracture with decreasing plate thickness. The relevant dimensions are shown in Fig. 1. This leads to the conclusion that BMG plates below a certain critical thickness can achieve the needed number of shear bands to demonstrate significant bending ductility. This thickness-dependent bending ductility is a property of BMGs that is distinct from crystalline metal alloys.

Due to the often limited glass-forming ability of many BMGs, standard products like rods and plates can often only be produced with diameters or thicknesses less than ~10–15 mm; hence, most bending tests are done on relatively thin rectangular plates or square bars. Furthermore, fracture toughness tests are often solely done on single-edge notched-bend (SE(B)) samples of relatively small dimensions. Although SE(B) samples are among the recommended specimen geometries in the ASTM standards for measuring the fracture toughness of materials (E399, E1820) [23,24], the size requirements found in those standards are based on the behavior of common crystalline metals, such as steel, aluminum and titanium alloys. Furthermore, the minimum size limitations of both the K_{Ic} E399 standard and the J-integral-based E1820 standard do not distinguish between BMG samples that are above or below a certain critical bending thickness. Also, J-calculations of plastic contributions by E1820 assume strain hardening while metallic glasses typically show local strain softening behavior in tension and compression with strain localization often in a single shear band [20,25–27]. As metallic glasses clearly show very different deformation behavior from crystalline metals, the question arises whether current ASTM standard sample-size restrictions can be applied to determine a sample geometry-independent measure of the fracture toughness for BMGs. Stated another way, are new sample-size requirements needed to account for the distinct size-dependent bending ductility behavior and strain softening behavior of BMGs?

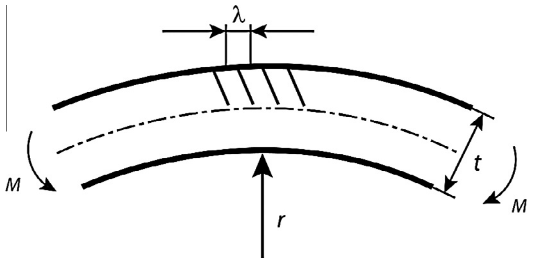

Fig. 1. Bending ductility of bulk metallic glasses. Conner et al. [21,22] have shown that BMG samples below a certain critical thickness, t, are capable of preventing catastrophic failure by the formation of multiple shear bands. The spacing of the shear bands, λ, decreases with increasing bending moment, M, and decreasing radius, r, leading to a more ductile behavior of the BMG.

To help answer these important questions, the present paper compares the fracture toughness of a $Zr_{52.5}Cu_{17.9}Ni_{14.6}Al_{10}Ti_5$[2] bulk metallic glass using SE(B) samples with various sample sizes and compact-tension (C(T)) samples with dimensions well above the critical bending thickness of this material. Furthermore, results generated by applying the most stringent sample-size limitations of plane strain K_{Ic} testing, as dictated by ASTM standard E399, are compared with those that follow the less restrictive size criteria of ASTM standard E1820 for J-integral-based fracture toughness testing.

2. Background

The size requirements for a valid linear-elastic K_{Ic} test require that loading conditions are essentially elastic, i.e. that the crack-tip plastic zone size, r_y, is small enough to be ignored – at least an order of magnitude smaller than the in-plane dimensions of crack size, a, and uncracked ligament width, b – to guarantee a state of small-scale yielding with K as the appropriate description of the crack-tip field. Additionally, for a single-value characterization of toughness, a state of plane strain must prevail, which is achieved when r_y is at least an order of magnitude smaller than the out-of-plane dimension of the sample thickness, B. In the latter case, a recent study has demonstrated that plane stress conditions can lead to much higher fracture toughness values in BMGs [28].

Fig. 2 shows the relevant sample dimensions and, based on testing of various polycrystalline alloys (mainly steel, aluminum, and titanium alloys), the above considerations led to the empirically determined size requirements for K_{Ic} testing used in ASTM standard E399 [23]:

$$a, b, B \geqslant 2.5\left(\frac{K_Q}{\sigma_{YS}}\right)^2 \tag{1a}$$

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[1] The effect of the notch root radius in artificially inflating the apparent fracture toughness of polycrystalline metals has been known since the 1970s [18]; however, this effect appears to be far more pronounced in BMGs [19,20].

[2] All compositions are given in terms of atomic percent.